AD-A161 292 ELECTROMAGNETIC SENSOR ARRAYS FOR NONDESTRUCTIVE EVALUATION AND ROBOT CON..(U) STANFORD UNIV CA EDWARD L GINZTON LAB OF PHYSICS B A AULD ET AL. OCT 85 1/1

UNCLASSIFIED AFOSR-TR-85-0970 F49620-84-C-0095 F/G 14/2 NL

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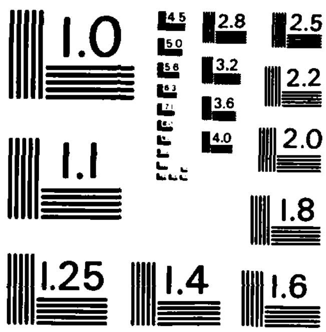


MICROCOPY RESOLUTION TEST CHART
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SECURITY CLASSIFICATIC

# AD-A161 292

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REPORT DOCUMENTATION PAGE

**1a. REPORT SECURITY CLASSIFICATION**
Unc

**1b. RESTRICTIVE MARKINGS**

**2a. SECURITY CLASSIFICATION AUTHORITY**

**2b. DECLASSIFICATION/DOWNGRADING SCHEDULE**

**3. DISTRIBUTION/AVAILABILITY OF REPORT**
Distribution is Unlimited
Approved for public release; distribution unlimited.

**4. PERFORMING ORGANIZATION REPORT NUMBER(S)**

**5. MONITORING ORGANIZATION REPORT NUMBER(S)**
AFOSR-TR- 85-0970

**6a. NAME OF PERFORMING ORGANIZATION**
Stanford University

**6b. OFFICE SYMBOL** *(If applicable)*

**7a. NAME OF MONITORING ORGANIZATION**
Air Force Office of Scientific Research

**6c. ADDRESS** *(City, State and ZIP Code)*
Edward L. Ginzton Laboratory
Stanford, Ca. 94305

**7b. ADDRESS** *(City, State and ZIP Code)*
Bolling AFB, DC 20332-6448

**8a. NAME OF FUNDING/SPONSORING ORGANIZATION**
AFOSR

**8b. OFFICE SYMBOL** *(If applicable)*
NE

**9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER**
F49620-84-C-0095

**8c. ADDRESS** *(City, State and ZIP Code)*
SAME as 7b

**10. SOURCE OF FUNDING NOS.**

| PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT NO. |
|---|---|---|---|
| 61102F | 2306 | A2 | |

**11. TITLE** *(Include Security Classification)* ELECTROMAGNETIC SENSOR ARRAYS FOR NONDESTRUCTIVE EVALUATION AND ROBOT CONTROL

**12. PERSONAL AUTHOR(S)**
B.A. Auld, J. Kenney, T. Lookabaugh and M. Gimple

**13a. TYPE OF REPORT**
Annual

**13b. TIME COVERED**
FROM 9/1/84 TO 8/31/85

**14. DATE OF REPORT** *(Yr., Mo., Day)*
October 1985

**15. PAGE COUNT**
21

**16. SUPPLEMENTARY NOTATION** The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the AFOSR or the U.S. Government.

**17. COSATI CODES**

| FIELD | GROUP | SUB. GR. |
|---|---|---|
| | | |
| | | |

**18. SUBJECT TERMS** *(Continue on reverse if necessary and identify by block number)*
Sensors, Robotics, Inductive, Capacitive, arrays, proximity, edge recognition, tactile

**19. ABSTRACT** *(Continue on reverse if necessary and identify by block number)*


A conceptual base is being developed for the design of inductive and capacitive sensor arrays capable of providing multifunction sensing, including proximity, tactile and edge recognition. Flaw detection and characterization is also included. The physical base for design is the electromagnetic reciprocity relation, which permits configuration of the probe structure to achieve desired performance characteristics. In this report the design, construction and testing of a novel 5-coil inductive sensor is described, and experimental results are given for its edge sensing function.




**20. DISTRIBUTION/AVAILABILITY OF ABSTRACT**
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

**21. ABSTRACT SECURITY CLASSIFICATION**
Unclassified

**22a. NAME OF RESPONSIBLE INDIVIDUAL**
Maj [redacted] Hager

**22b. TELEPHONE NUMBER** *(Include Area Code)*
(202) 767-4933

**22c. OFFICE SYMBOL**
NE

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE. Unclassified

ELECTROMAGNETIC SENSOR ARRAYS FOR
NONDESTRUCTIVE EVALUATION & ROBOT CONTROL

by

B.A. Auld, J. Kenney, T. Lookabaugh, and M. Gimple

Annual Report
on research performed under
Contract: F49620-84-C-0095
Principal Investigator
B. A. Auld



Edward L. Ginzton Laboratory
W.W. Hansen Laboratories of Physics
Stanford University
Stanford, California 94305



October 1985

# I Objectives of the Research

Over the three-year period of the proposed research, modeling, analysis, design, and concept-testing experiments will be carried out at Stanford University to establish a scientific base and design philosophy for electromagnetic sensor arrays. Both inductive (eddy-current) and capacitive sensors will be studied. Applications goals are nondestructive evaluation and robot control. This research will be coordinated with a closely related effort proposed by SRI International. The specific schedule of tasks is summarized as follows:

*First Year*: Field-, interaction-, and system-models will be analyzed for rudimentary (2-element) sensors. Concepts will be tested experimentally.

*Second Year*: One-dimensional scanned and staring modeling will be developed and specific designs generated for scanned arrays.

*Third Year*: Specific designs will be generated for staring arrays, and modeling of two-dimensional arrays will be developed.

# II Status of Research Effort

## (a) Introduction

Eddy current probes have been used for decades to detect flaws in metal objects. These probes are unusually sensitive to changes in the proximity distance to the test surface, and special techniques must be used to suppress this proximity signal when searching for flaws. More recently this proximity effect of a test coil has been recognized as useful for robotic sensing, and several sensors of this type are on the market. However, recent scientific advances in the design of eddy current flaw detection probes have not yet been applied to eddy current robotic sensors. A similar situation exists in connection with capacitive sensors, which were initially applied as intruder sensors and, more recently, to a small degree, as robotic proximity sensors. A common criticism of these circuit-type sensors is that they do not provide sufficient spatial selectivity to be useful in robotic applications. However, recent studies of flaw detection probes have shown that desirable detection properties can be designed into the probe by using spatial frequency analysis to determine the optimum probe geometry for the task at hand. In this approach the probe is treated as a spatial filter, much like optical signal processing components, but in this case the

electromagnetic field is nonradiating (or quasistatic). The purpose of this research is to develop a conceptual base and associated technology for electromagnetic sensor arrays applied to automated manufacturing, maintenance, and NDE. Concepts and theory of this research are discussed in this report, while the experimental system and measurements are presented in Ref. 1.

### (b) Sensor arrays and spatial frequency processing

In the quasistatic regime relevant here, array design follows quite different principles than in the case of optical and radio arrays. For a quasistatic array, the field is derivable from a scalar potential satisfying Laplace's equation. This means that there is no diffraction, and consequently no diffraction limit to the spatial resolution of the sensor array. It is for this reason that eddy current probes operating at frequencies below 1 MHz can resolve flaws spaced closer than one millimeter. Spatial resolution is determined by the geometry of the probe, rather than the electromagnetic wavelength. Although this has long been known, there exists no theoretical and conceptual base governing the principles and design of quasistatic arrays. The importance of creating such a base can be demonstrated by a simple example. Since a quasistatic field is derivable from a scalar potential satisfying Laplace's equation, a sinusoidal variation along one direction must be accompanied by an exponential variation along the orthogonal direction. By controlling the period of the sinusoidal variation along the first direction one can control the exponential decay along the orthogonal direction, in this way varying the spatial extent of the field in the second direction. If the first direction is along the plane of a quasistatic array, a sinusoidal variation can be simulated by adjusting the amplitudes and phases of the array element excitations. The distance the field extends out in front of the array is thereby determined by the excitation pattern of the array elements. To fully exploit and optimize this "ranging" function the relationship between the field of the array and its geometrical structure must be fully understood. This requires a complete analysis of the spatial Fourier spectrum (or spatial frequency content) of the field, and control of this spectrum by tailoring the array geometry.

The previous paragraph described one possible operating mode for a quasistatic array, controllable ranging of the depth of the array field (i.e., the "zoom" effect). In this mode the array is operated with all array elements simultaneously excited—the

*staring mode*. Quasistatic arrays may also be operated in the *scanning mode* where individual elements or groups of elements are sequentially excited. Both types of operating mode are useful for either inspection or sensing applications. The *staring mode* controls the shape and extent of the interrogating field generated by the array (analogous to beam shaping and focusing in a radiation array), while the *scanning mode* electronically controls the spatial position of the interrogating field. It is also possible to combine the two functions by scanning a group of excited elements that, itself, operates in the staring mode.

Why should electromagnetic arrays be used for flaw inspection and for robotic sensing? In both applications electromagnetic probes exhibit good sensitivity to structural features and proximity effects. They also offer advantages over optical and ultrasonic probes in hostile environments such as opaque liquids and outer space. In NDE, electromagnetic sensor arrays provide good sensitivity and flaw inversion capability, rapid scanning without mechanical motion, and ranging and spatial frequency filtering for target enhancement. As robotic sensors, these arrays offer fast electronic scanning and ranging, highly selective sensing (as compared with robot vision), insensitivity to optical and electrical noise (with proper filtering and choice of the operating frequency), ability to detect optically-hidden features, and very high sensitivity to proximity and touch. On the other hand, electromagnetic robotic sensors do not furnish the detailed image information easily obtained with a vision system. The two types of sensors are, in fact, complementary. Vision provides the robot with detailed information, at a relatively long distance, about the shape and orientation of the object. Quasistatic electromagnetic sensors are best suited to the rapid delivery of very specific information about proximity, and feature position, or orientation at short distances (between 0" and 12"). Electromagnetic sensors also have the feature of being sensitive to the material properties of the object being sensed. This has often been stated in the past as a disadvantage for robotic applications. In the case of a metallic object it is well known in the NDE community that the phase angle of the proximity (or liftoff) signal gives information about the material conductivity, while the amplitude of the signal gives information about the proximity distance. Sensitive proximity sensing of a nonmetallic object requires, on the other hand, use of a capacitive probe. (Such a probe can, of course, also be used to measure the proximity of a metallic object.) With integrated circuit

techniques, very compact combinations of inductive and capacitive sensor arrays can be envisioned, and such hybrid array systems clearly have the capability of rapidly providing very selective information about both the proximity distance *and* the material properties of the object. It will also be seen in the next section that these systems can be modified so as to furnish both proximity and *tactile* information in the same structure.

### (c) Rudimentary arrays for edge and position sensing

Figure 1 shows a type of eddy current probe, the reflection probe, commonly used in NDE. It is shown at the left of the figure, and consists of a large drive coil plus two small pickup coils connected in phase opposition. This geometry gives high sensitivity and spatial resolution for flaw detection. At the same time it cancels out changes in transmission from terminal 1 to terminal 2 due to changes in the proximity spacing between the probe and the test piece. If, on the other hand, the pickup coils are connected in phase addition the transmission signal is very sensitive to the proximity distance. Both of these signals can be read simultaneously from the probe by using a standard hybrid coil connection. The difference signal on the left can then be used to identify and locate object features such as edges, while the sum signal on the right gives a measure of proximity. If a compliant dielectric layer is placed between the probe and the object, as shown in the figure, the sum signal will also give a measure of tactile pressure after contact is made with the object. This example clearly illustrates the facility with which electromagnetic sensors can deliver in real time several specific sensor output parameters. A capacitive analog of this sensor, with the same features, is shown in Fig. 2. This second version is, perhaps, preferable because of its greater suitability for integrated circuit fabrication.

The goals of the first year of research in this area are to develop a theory describing the interaction of the probe in Fig. 1 with the test object in Fig. 3, and to test the theory experimentally. This is a collaborative effort with SRI International [1]. The ultimate goal is to design and test sensor arrays, with array elements consisting of individual coils (or capacitors) or compound structures such as those in Figs. 1 and 2. The test object in Fig. 3 was chosen so that experiments could be performed on two basic canonical recognition problems, edge-position detection and

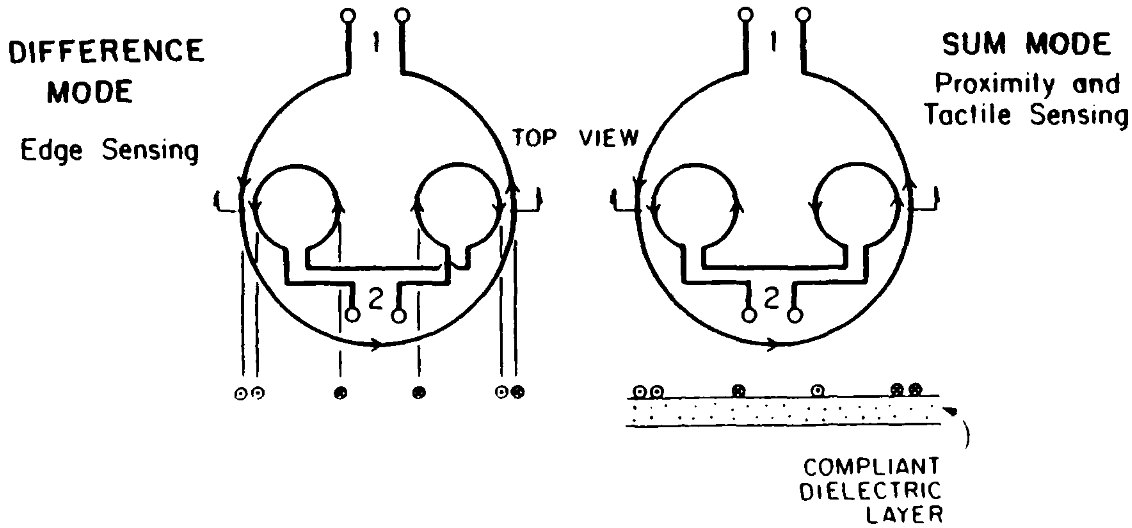



**FIGURE 1**

Reflection type inductive probe array for edge, proximity and tactile sensing.

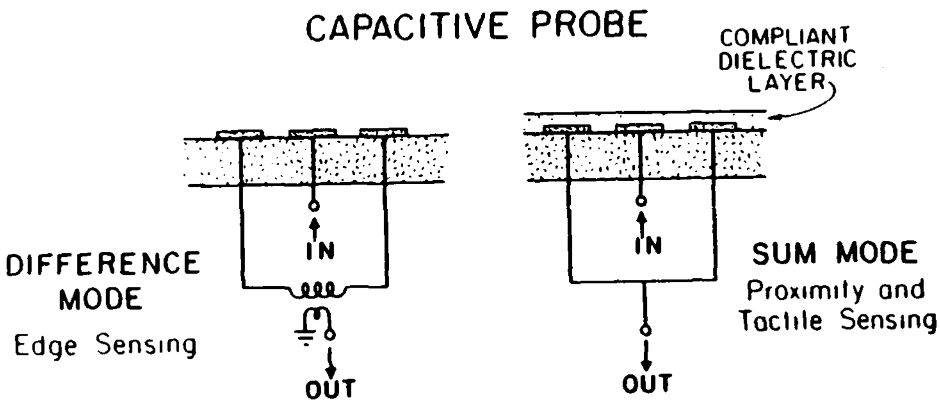



**FIGURE 2**

Capacitive probe array for edge, proximity and tactile sensing.

edge-orientation detection. The edge in question is a small amplitude step milled in an aluminum plate. In all cases the step height is on the order of a few thousands of an inch. Changes in proximity distance in this range give very large signals in a electromagnetic probe, but would be difficult to detect with a vision syst( n unless special side lighting is used. If the edge sample is placed under the difference-mode probe on the left of Fig. 1, the different electromagnetic surface impedances, $Z_s$ and $Z'_s$, on either side of the edge in Fig. 3 cause changes in coupling between the drive coil and the two small pickup coils. When the edge is parallel to the horizontal axis in the figure the changes for the two pickup coils are the same, and the edge signal cancels at port 2. Orientation of the edge parallel to the vertical axis, however, gives different couplings into the pickup coils, and a net edge signal appears at the output port. This signal is maximum when the edge is midway between the two pickup coils. The probe is therefore sensitive to both position and orientation of the edge. For a vertical edge, the probe has *maximum* sensitivity to edge position and *minimum* sensitivity to edge orientation, and conversely for a horizontal edge. From these observations it follows that an ideal probe for simultaneously detecting both the position and the orientation of an edge has the form shown on the left of Fig. 1, but with an extra set of pickup coils aligned vertically. For a horizontal edge the horizontal pair of pickup coils detects angle variations and the vertical pair of pickup coils detects position variations (Fig. 4). Extension to the analog capacitive probe of Fig. 5 is obvious. With a probe of this type a robot hand could follow an edge by using the position and angle outputs to control its motion, resetting the two sets of pickup coils perpendicular and parallel to the edge at each step of the motion. To perform this tracking operation it would be convenient to have a zero position output when the probe is centered over the edge. One approach for generating such a signal is described below.

The $\Delta Z$ formula for a single-port eddy current probe is used in Reference 2. For the difference mode probe of Fig. 1 the corresponding general formula is [3]

$$\Delta Z_{12} = \frac{1}{I^2} \int (E'_1 \times H_2 - E_2 \times H'_1) \cdot \hat{n}\, dX dY \qquad (1)$$

where, as in the reference cited, the unprimed fields are for a smooth surface and the primed fields are for the stepped surface. A unit vector normal to the test object surface is denoted by $\hat{n}$. The subscripts 1 and 2 on the fields in Eq. (1)

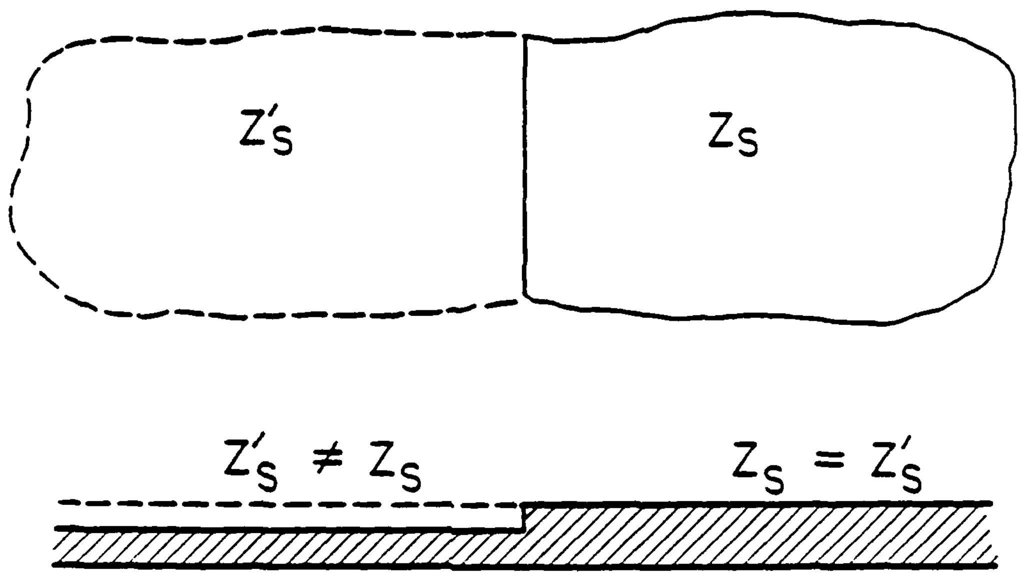



**FIGURE 3**

Test sample for edge sensing experiments.

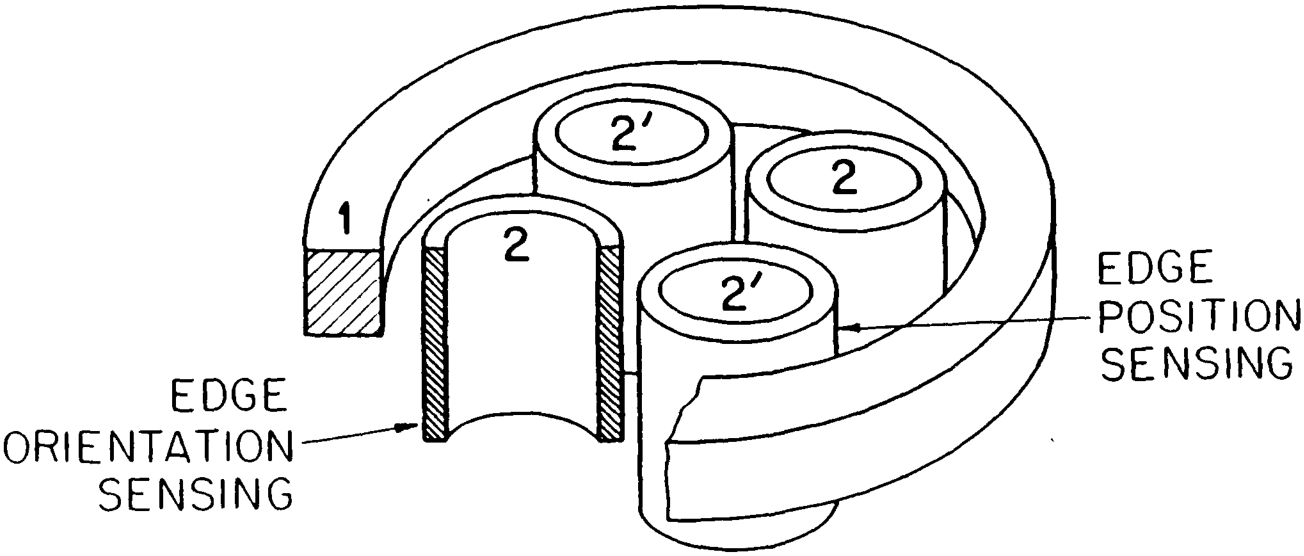



**FIGURE 4**

Five-coil inductive probe for position and orientation sensing of an edge. Coils 2' are for position sensing; coils 2 for orientation sensing.

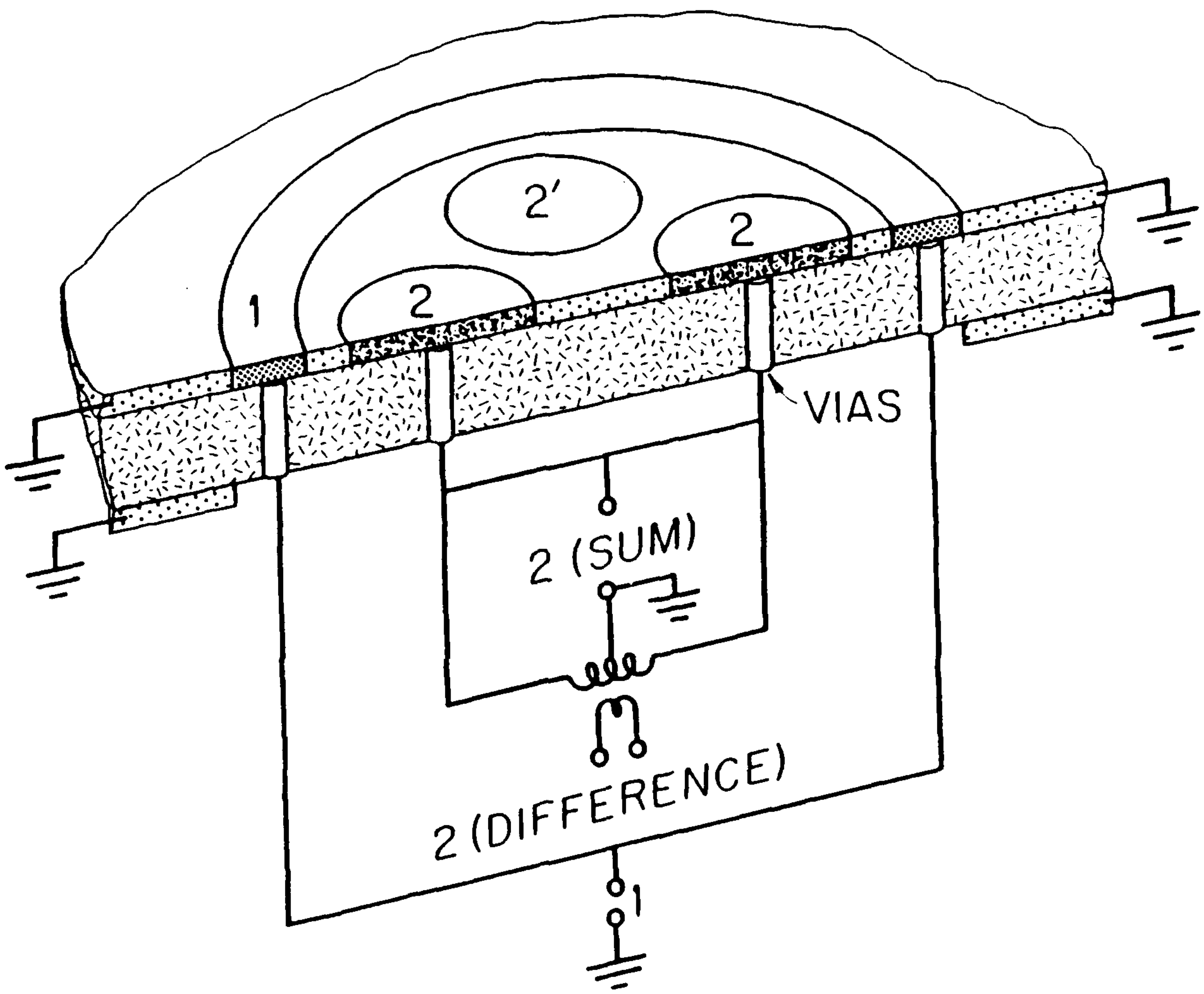



**FIGURE 5**

Capacitive version of Fig. 8.

indicate that the fields are those produced by applying current $I$ at ports 1 and 2, respectively, in Fig. 1. When the probe dimensions are large compared with the skin depth of the aluminum test sample the impedances $Z_s$ and $Z'_s$ in Fig. 3 can be defined for plane waves traveling normal to the surface [3], except in a narrow band near the step on the test object shown in the figure. If this correction is ignored in a first approximation, the electric field can be related to the magnetic field by the electromagnetic impedance at each point on the surface. This reduces Eq. (1) to

$$\Delta Z_{12}(X_0, Y_0) = \frac{1}{I^2} \int \Delta Z_s(X,Y)\{H_1 \cdot H_2(X,Y,X_0,Y_0)\}\, dX dY \qquad (2)$$

where $\Delta Z_s$, the difference between the primed and unprimed surface impedances, is zero on the right-hand side of Fig. 3. (It should be noted that the magnetic fields in Eq. (2) contain only components parallel to the surface of the test object.) The variables $X_0$ and $Y_0$ define the position of the center of the probe in a coordinate system in the plane of the surface. A second approximation used in writing Eq. (2) is to replace the primed magnetic field by the unprimed field. This is valid for the small amplitude steps considered here. One final comment should be made about the form of Eq. (2). It is seen to have the form of a convolution integral, in which the scalar product of the coil fields is the kernel. Figure 6 shows the form of this kernel, with $X_0, Y_0 = 0$, for the actual probe used in experiments [1].

### (d) Probes for edge position and orientation sensing

Figures 4 and 5 showed 5-element rudimentary inductive and capacitive arrays for edge detection and tracking by a robot hand. In the capacitive figure the hybrid circuit for simultaneous readout of edge and proximity (or tactile) signals is also shown explicitly. Only the inductive version has, so far, been fabricated and tested. Details of the experiments are presented in the companion paper, but Fig. 7 gives a comparison of theory and experiment for the edge orientation sensing. One adjustable parameter was used, since the instrumentation was not calibrated for magnitude of the signal.

### (e) More sophisticated array processing

The above discussion touched on only the simpler aspects of quasistatic array processing. Some possible improvements will be considered here. As the probe on

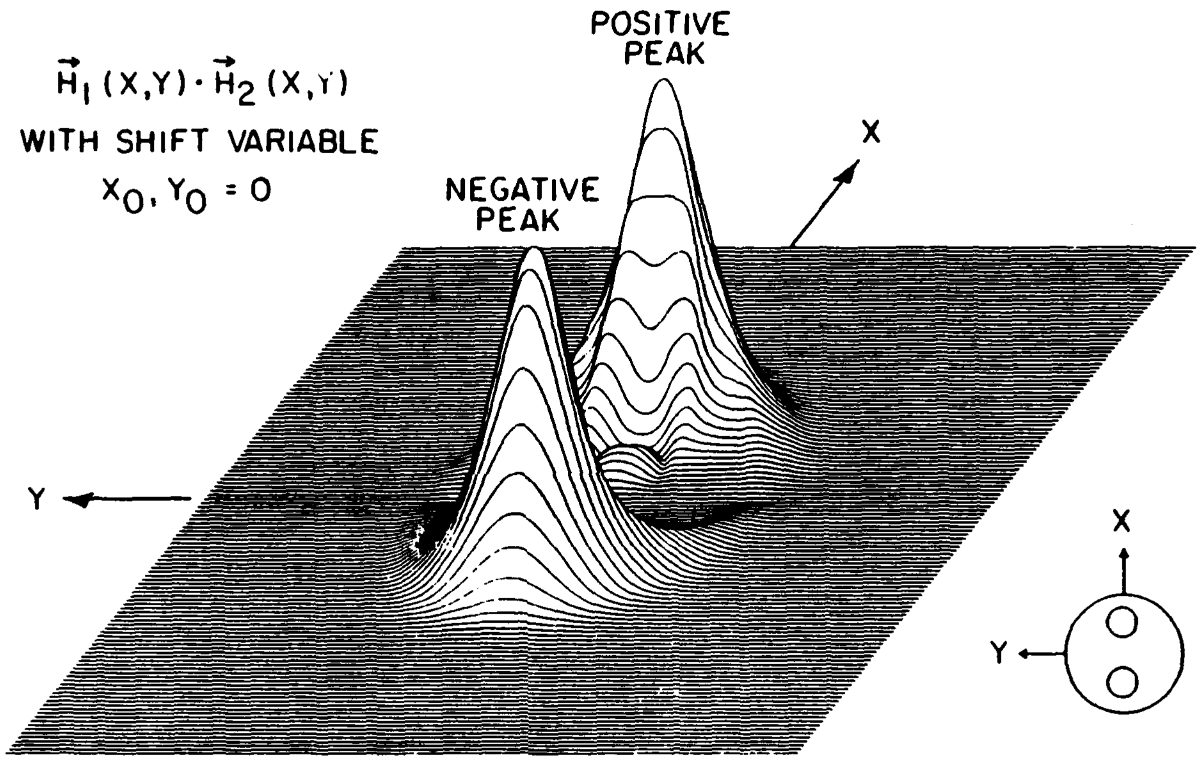



**FIGURE 6**

Kernel of the $\Delta Z$ integral for the probe of Fig. 1.

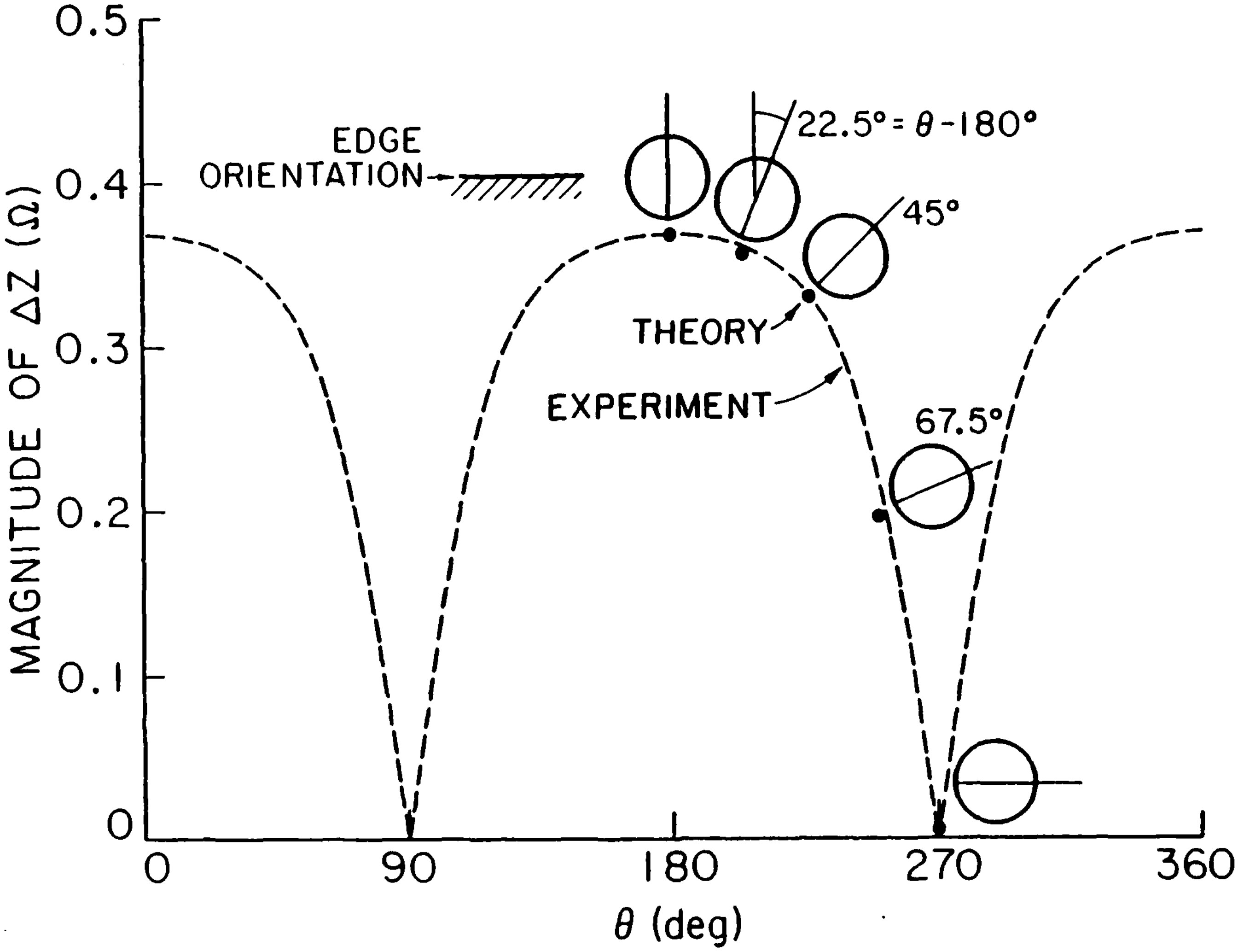



**FIGURE 7**

Comparison of theory and experiment for edge orientation sensing with the probe of Fig. 4.

the left of Fig. 1 passes over a vertical edge the output signal reaches a *maximum* when the probe is centered over the edge. For robot control it is desirable to have a sensor that generates a null signal when the hand is positioned over the edge. Fig. 8 illustrates a method for achieving this kind of signal in a capacitive version of the probe. The top part of the figure shows how the two capacitive pickup signals combine to give a *differential* output that is maximum when $X_0 = 0$. At the bottom of the figure is shown a differential sensing probe that gives a null when it is centered over the edge. This is accomplished by combining two 3-electrode probes, shifted in position relative to each other, and combining their outputs in phase opposition. The result is the discriminator curve shown by the heavy line at the bottom of the figure.

Another interesting signal processing function achievable with a quasistatic array is electronic ranging. This is illustrated for a multielectrode linear capacitive array in Fig. 9. The principle has already been discussed above. Changing the phasing of the electrodes in groups, as shown, changes the distance of penetration of the array field in front of the array. This feature could be used to pulse the depth of the interrogating field in and out as the robot hand approaches an object, thereby providing faster and more accurate information about the rate of closing.

### (f) Probe modeling concepts

Since the spatial resolution of a quasistatic electromagnetic sensor is determined by its size, the dimensions of its array elements must be small and accurately controlled. This points to the need for integrated circuit technology in fabricating such arrays, and therefore favors use of capacitive arrays. There has been very little development effort, as yet, on even single element capacitive sensors and virtually no detailed analytical modeling. Although every inductive array has a capacitive dual, the modeling formulas are quite different. Figure 10 illustrates this point for the single sensor geometry [3,4]. In an inductive probe the fields under the integral are defined for given *current* drive on the coil; in a capacitive probe the fields under the integral are defined for given *voltage* drive on the electrode. This rather simple difference makes capacitive sensors harder to treat analytically.

The difficulty inherent in analyzing a capacitive sensor probe is illustrated by Fig. 11. It was seen in the previous figure that, to evaluate $\Delta Y$ for a capacitive

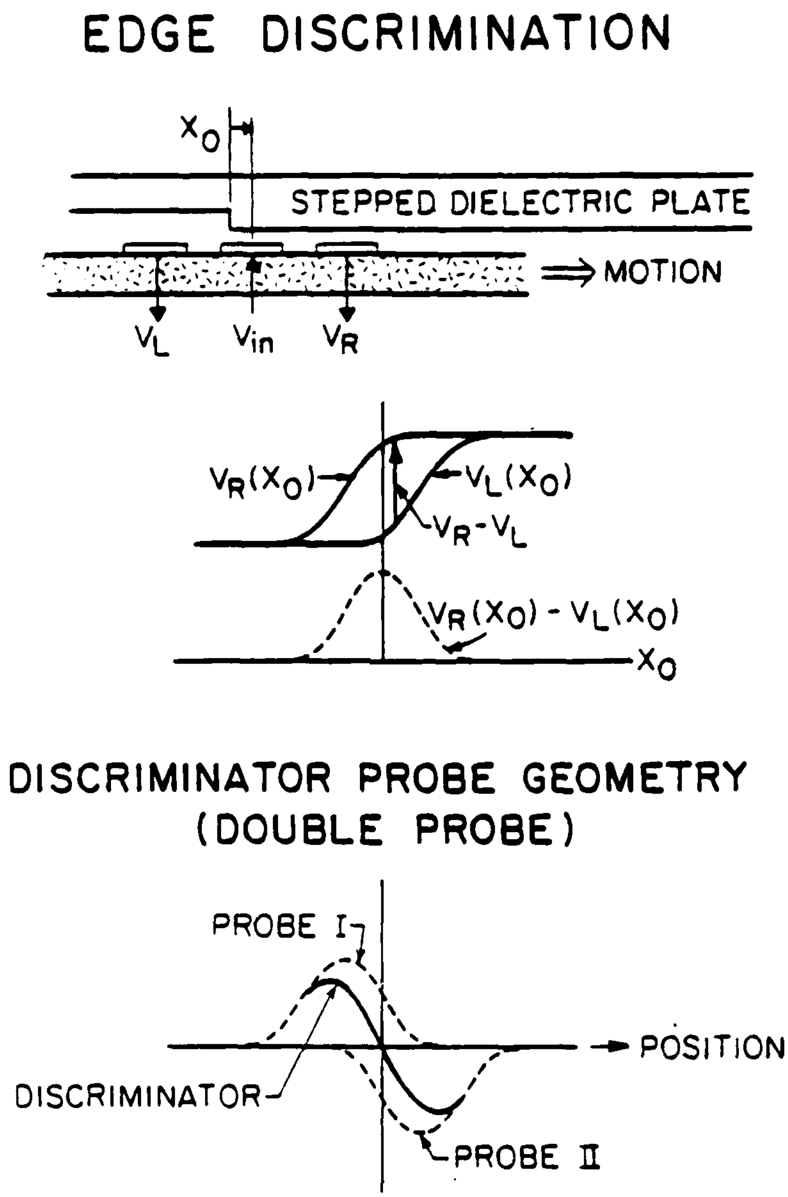



**FIGURE 8**

Capacitive discriminator probe for null detection of edge position.

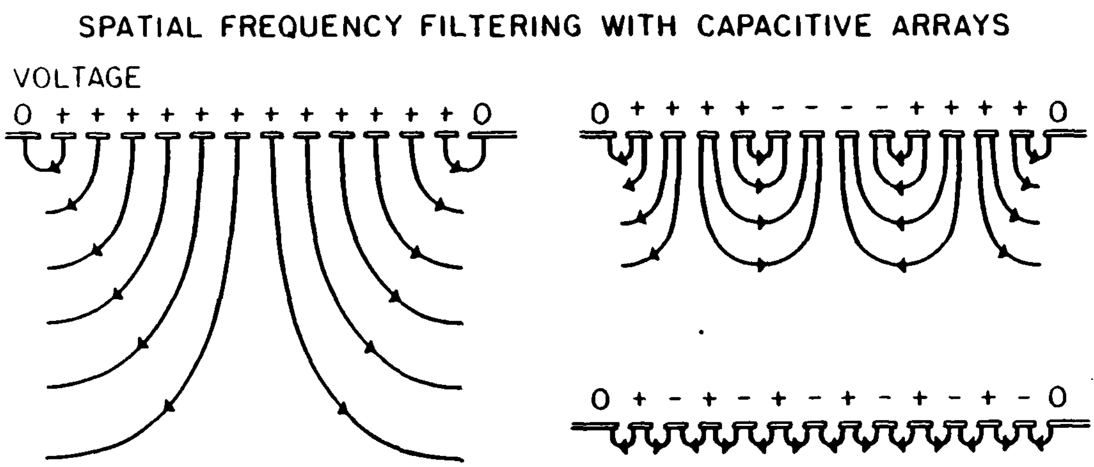



**FIGURE 9**

"Zoom" effect produced by varying the spatial frequency spectrum of a linear capacitative array.

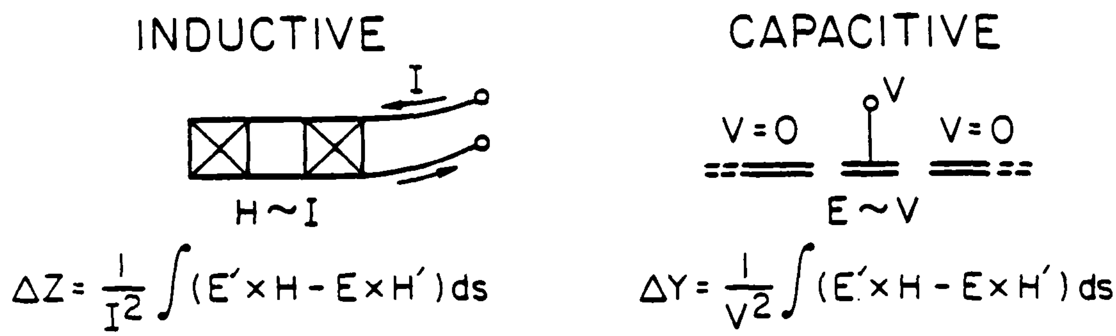
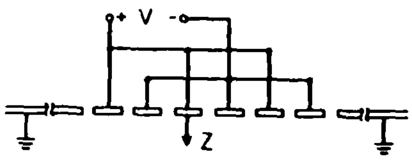



**FIGURE 10**

Comparison of the $\Delta Z$ formula for an inductive probe and the $\Delta Y$ formula for a capacitive probe.




$\nabla^2 \phi = 0 \qquad E = -\nabla\phi$

$\phi(X,Y)$ SPECIFIED AT $Z = 0$

**ANALYSIS OF CAPACITIVE ARRAYS**

1) EXPAND
$\phi(X,Y)$
IN 2-D FT (SPATIAL FREQUENCY ANALYSIS)
2) FIND EACH FT COMPONENT
3) SPATIAL FILTERING AND PATTERN RECOGNITION
4) ZOOMING AND DISTANCE RANGING

**FIGURE 11**

Procedure for analyzing capacitive arrays.

probe, the fields under the integral must be evaluated with a given voltage $V$ applied to the electrodes. In Fig. 11 this means that the electric potential is known only on the driven electrodes and the ground electrodes at $Z = 0$. To find the electric field generated by the array it is necessary to solve the electric potential problem in the space below the array. The difficulty is that the potential is not initially known at *all* points on the plane $Z = 0$. In particular, the potential is not defined in the gaps between the electrodes until the complete potential problem is solved. One approach to this difficulty is to estimate the potential variation in the gaps and then check the final solution for self-consistency. A saving feature of this approach is that the gap potentials contribute mainly to the higher spatial frequency components of the array field. These components decay very rapidly with increasing $Z$ in the figure, so that it is not necessary to accurately model the gap region.

### (g) Summary

An analytical base has been developed for calculating the performance of rudimentary electromagnetic sensor arrays (the 3-coil probe of Fig. 1 and the 5-coil probe of Fig. 4) in their application to edge position and orientation sensing. Theoretical predictions are in good agreement with experimental results.

Future plans include development of modeling theory for inductive sensor arrays operating in both the scanning and staring modes. An analytical base will also be created for capacitive duals of all these inductive arrays.

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4. B.A. Auld and M. Riaziat, J. Appl. Phys. **54**, 3509 (1983).

## III. List of Publications

B.A. Auld, J. Kenney, and T. Lookabaugh, "Electromagnetic sensor arrays—Theoretical studies," to appear in *Proceedings* of the Williamsburg Review of Progress in Quantitative Nondestructive Evaluation, June 1985.

B.A. Auld and A.J. Bahr, "A Novel Multifunction Robot Sensor," submitted for presentation at the 1986 International Conference on ROBOTICS AND AUTOMATION, San Francisco, April 14–17 1986.

## IV. Professional Personnel

B.A. Auld, Principal Investigator

T. Lookabaugh, Graduate Student

M. Gimple, Graduate Student

J. Kenney, Part Time Student Employee

## V. Interactions

B. A. Auld , J. Kenney, and T. Lookabaugh, "Electromagnetic sensor arrays—Theoretical studies", presented at Review of Progress in Quantitative NDE, Williamsburg, Virginia, June 1985.

## VI. New Discoveries

A novel multifunction robot sensor has been conceived and partialy reduced to practice. This sensor is capable of simultaneously providing the following sensing functions: (1) proximity, (2) edge position and orientation, (3) tactile, (4) material diagnosis, (5) flaw location and sizing. A patent disclosure is to be prepared.

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